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Elastic scattering of light from fluctuating exciton polarization of a quantum well in a semiconductor microcavity

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Abstract. A model of exciton polarization fluctuations due to randomly rough interfaces of a quantum well (QW) is proposed. On this basis, a theory of the resonant elastic scattering of light is developed for a random-thickness QW placed in a semiconductor microcavity. Numerical study of the cross-section shows that the light scattering induced by roughness with standard deviation height as small as 0.2 nm could be detected experimentally. An enhancement of backscattering intensity is predicted.

Introduction

Resonant splitting and enhancement of exciton polaritons in semiconductor microcavities (MC) [1] is realized assuming quantum wells (QW) to possess perfectly flat interfaces. Typical of real QWs are various imperfections whose most significant representative is random roughness of interfaces. The inhomogeneity-induced optic effects and light scattering, in particular, are expected to be of great importance in MCs. This work is aimed at treating the resonant elastic scattering of light from fluctuations of excitonic polarization in QWs, especially as it could occur in a MC arrangement.

1. Model

The basic element of the proposed model is a QW centered at $z = z_0$ inside a Fabry–Perot resonator (FPR) ($0 < z < d$) whose background dielectric constant is ε_2. Following [2], the QW interfaces $z = z_0 - \bar{L}/2 + \zeta_1(x)$ and $z = z_0 + \bar{L}/2 + \zeta_2(x)$ are assumed to be randomly rough. For random profile functions $\zeta_n(x)$ of the nth interface the mean value over the ensemble $\{\zeta_n\}$ is $\langle\zeta_n\rangle = 0$, with $\bar{L} = \langle L\rangle$ and $\delta L\,(x) = \zeta_2\,(x) - \zeta_1\,(x)$ being an average and a fluctuation of the QW thickness $L\,(x) = \bar{L} + \delta L\,(x)$. At a given frequency ω of light, an induced polarization associated with quasi-2D excitons of the QW is of the from

$$\mathbf{P}\,(\mathbf{r},\omega) = \widehat{\mathbf{y}}\cdot\left[P^0\,(z;\,Q,\omega) + \delta P\,(z;\,Q,\omega)\right]\cdot\exp\,(iQx)\,, \tag{1}$$

the same being true for the other electromagnetic field characteristics, whose tangential wavevector component Q conserves in passing a flat interface. In Eq. (1) P^0 corresponds to an "average" QW with the interfaces $z = 0$ and $z = \bar{L}$, and δP is due to the fluctuation $\delta L\,(x)$. When the random thickness $L\,(x)$ keeps nearly constant within an area whose lateral sizes exceed the exciton Bohr radius a_B, it defines locally the exciton transition energy $\hbar\omega_0\,[L\,(x)]$, which is mainly defined by the energies of electron and hole confinements in the QW. If $\sqrt{\langle\delta L^2\rangle} \ll \bar{L}$, or $\sqrt{\langle\delta\omega_0^2\rangle} \ll \bar{\omega}_0$, a random variation $\delta\omega_0\,(L) = \omega_0\,(L) - \bar{\omega}_0$ relative to the average $\bar{\omega}_0 = \langle\omega_0\,(L)\rangle$ is

$$\delta\omega_0\,(x) \simeq -\Omega\cdot\delta L\,(x)\,/\bar{L} \simeq -2\pi^2\cdot\eta\cdot(R_{\mathrm{x}}/\hbar)\cdot\left(a_B/\bar{L}\right)^2\cdot\delta L\,(x)\,/\bar{L}, \tag{2}$$

where $\eta \sim 1$, and R_x is the exciton Rydberg energy. In turn, if $\sqrt{\langle \delta\omega_0^2 \rangle} < \gamma$, with γ being the nonradiative decay rate of the exciton, the term δP is written as a linear function of $\delta L(x)$ [2].

Next, we assume the FPR to be sandwiched in between distributed Bragg reflectors (DBR), the dielectric constants of the outer half-spaces $z < -l_1$ and $z > d + l_2$ to be ε_1 and ε_3, respectively, l_1 and l_2 being the DBR thicknesses. The amplitudes of electromagnetic waves in the media, specified by ε_m, are related to each other with the transfer matrices of the DBRs. For the waves of type (1) $Q = \sqrt{\varepsilon_m} k_0 \sin\theta_m$, where θ_m is the propagation angle in the mth medium, with the z-component of the wavevector being $k_m \equiv k_m(Q) = \sqrt{\varepsilon_m k_0^2 - Q^2}$, and $k_0 = \omega/c$.

2. Quasi-2D excitons in an "average" QW

Given the regular term P^0 in Eq. (1) and the coefficients $r_1(Q)$ and $r_2(Q)$ of light reflection back to the FPR from its interfaces $z = 0$ and $z = d$, respectively, the complex frequency of the exciton transition in the "average" QW is expressed as

$$\omega_0(Q) = \bar{\omega}_0 + \Gamma \cdot \mathrm{Im}F(z_0) - i\{\gamma + \Gamma \cdot [1 + \mathrm{Re}F(z_0)]\}, \tag{3}$$

where

$$\begin{aligned} \Gamma(Q) &= \Gamma_0 \cdot \sqrt{\varepsilon_2} k_0 / k_2, \qquad (4) \\ F(z_0, Q) &= \{r_1 \exp(2ik_2 z_0) + r_2 \exp[2ik_2(d - z_0)] + 2r_1 r_2 \exp(2ik_2 d)\}/D, \\ D(Q) &= 1 - r_1 \cdot r_2 \cdot \exp(2ik_2 d). \end{aligned}$$

The difference $\omega_0(Q) - (\bar{\omega}_0 - i\gamma)$ from Eq. (3) gives the excitonic radiative energy shift and damping rate, the former tends to zero and the latter to the value (4), if $r_1 = r_2 = 0$, i.e. the QW is placed in a homogeneous semiconductor.

3. Reflectivity

When a light wave with the wavenumber Q is incident along the z-axis, the reflection coefficient r of the whole system (a MC with a QW) is

$$\begin{aligned} r(Q) &= \rho_1 + \tau_1 t_1 \left[i\Gamma\Phi^2(z_0)\Delta^{-1}D^{-1} + r_2 \exp(2ik_2 d) \right] D^{-1}, \qquad (5) \\ \Delta(Q) &= \omega_0(Q) - \omega, \qquad (6) \\ \Phi(z, Q) &= \exp(ik_2 z) + r_2 \exp(2ik_2 d) \exp(-ik_2 z). \end{aligned}$$

In Eq. (5) ρ_1 is the reflection coefficient of a single left DBR ($-l_1 < z < 0$) surrounded by media ε_1 and ε_2, when light is incident along the z-axis. For the same arrangement, τ_1 and t_1 are the transmission coefficients of light propagating along the z-axis and against it, respectively.

4. Scattering of light

The scattering problem originating in a random polarization δP, Eq. (1), is solved perturbatively [2]. When a photon is incident at an angle θ_1 on the MC from the left, the

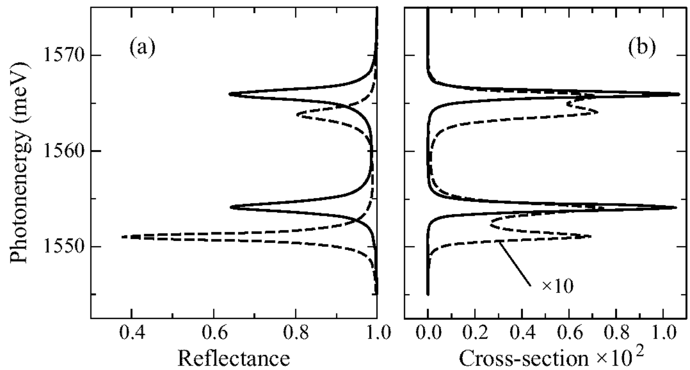

Fig. 1. Reflectance $|r|^2$ (a) and the cross-section of elastic scattering $d\sigma/d\theta_1'$ (b) calculated as functions of photon energy $\hbar\omega$ from Eqs. (5) and (7) with the following parameters of a GaAs-based heterostructure: $\hbar\bar{\omega}_0 = 1.56$ eV, $\hbar\Gamma_0 = 0.25$ me, $\hbar\gamma = 1$ meV, $\hbar\omega_c = 1.553$ eV (MC resonance energy), $\hbar\Omega = 50$ meV, $\bar{L} = 14$ nm, $h = 0.2$ nm, $\Lambda = 150$ nm. Solid curve in (b) corresponds to the angles $\theta_1 = -\theta_1' = 18^\circ$ (backscattering), and dashed one to $\theta_1 = 18^\circ$, $\theta_1' = 9^\circ$, for the corresponding curves in Fig. 1(a) the incidence angles coincide with the above $|\theta_1'|$.

dimensionless cross-section for its backward scattering at an angle θ_1' can be obtained to the lowest order in ξ_n (Born's approximation) as follows

$$\frac{d\sigma}{d\theta_1'} = W(Q' - Q)\frac{\cos^2\theta_1'}{\cos\theta_1}\left|SS'\Phi(z_0)\Phi'(z_0)\right|^2\left|D'\right|^{-2}\left|M_I M_{II}'\right|^2. \tag{7}$$

Here, prime denotes the values for scattered light with Q', in contrast to those for incident light with Q, and $W(Q' - Q)$ is proportional to the Fourier transform of a correlation function $\left\langle \delta L\left(x - x'\right)\delta L\left(0\right)\right\rangle$. For Gaussian correlator

$$\left\langle \xi_n(x)\,\xi_{n'}\left(x'\right)\right\rangle = \delta_{nn'}h^2\exp\left(-\left|x - x'\right|^2/\Lambda^2\right)$$

$$W(Q' - Q) = \frac{\sqrt{\varepsilon_1}k_0\Lambda h^2}{\sqrt{\pi}\bar{L}^2}\exp\left(-\left|Q' - Q\right|^2\Lambda^2/4\right), \tag{8}$$

where Λ is the transverse correlation length and h is the r.m.s. height of roughness. The excitonic resonant features are described by the spectral function

$$S(Q,\omega) = \sqrt{\Gamma(Q)\,\Omega}/\Delta(Q) \tag{9}$$

with (2), (4), (6) inserted, and the transformation coefficients $M_l(Q)$ are defined by the transfer matrices of the DBRs.

5. Calculation and summary

The calculated spectra of reflection and elastic scattering of light are shown in Fig. 1 for the light-hole quasi-2D exciton of a GaAs/AlGaAs QW in a MC. Reflectance (Fig. 1(a)) reveals a strong resonant coupling between an electromagnetic mode of the MC and a quasi-2D exciton of the QW depending on the incidence angle. Typical of the manifestation of

exciton-photon interaction is sharing the mode intensities, which become equal just at the resonance (compare the solid and dashed curves in Fig. 1(a)). Figure 1(b) gives evidence that this effect could result in an enhancement of the maximum intensity of scattered field by about an order of magnitude: compare the solid curve related to strict backward (anti-specular) scattering under the resonance conditions with the dashed one corresponding to different incidence and scattering angles. The latter angle difference is responsible for a doublet spectral structure of radiated field near each of the resonances, whose two components are given by the spectral factors (9) of one incident and one scattered waves. In general, the scattering probability at a resonance is defined by the parameter $\left(h/\bar{L}\right)^2 \ll 1$ and is estimated here as $\sim 10^{-2}$ under the usual conditions and $k_0\Lambda \sim 1$, similarly to a single QW ($r_1 = r_2 = 0$) [2]. Comparison of this result with the corresponding experimental cross-sections available for rough semiconductor surfaces [3] allows to conclude the resonant scattering of light to be detectable for QW roughness with the standard deviation height $h \sim 0.2$ nm.

References

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